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Pastoral land-use of the Indus Civilization in Gujarat: faunal analyses and biogenic isotopes at Bagasra

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ABSTRACT

The Indus Civilization (2600–1900 BC) in Gujarat is characterized by a series of small yet monumentally walled settlements located along trade and travel corridors. The manufacture and use of typically Harappan material culture at these settlements demonstrates that many residents of these sites participated in exchange and interaction networks that linked them to distant Indus cities. Less is known, however, regarding the ways in which the residents of these sites were situated into their local landscapes. Here we combine previously published faunal analyses from the small walled settlement of Bagasra in the Indian state of Gujarat, with a preliminary investigation of intra- and inter-individual variation in the ratios of biogenic isotopes of strontium ($^{87}Sr/^{86}Sr$), carbon ($\delta^{13}C$), and oxygen ($\delta^{18}O$) in the tooth enamel of domestic animals consumed at the site. $^{87}Sr/^{86}Sr$ ratios in the teeth of sheep and goats exhibit little intra- or inter-individual variation suggesting that most were raised locally while greater inter-individual variation in the teeth of cattle suggesting that nearly half of these animals were either raised further afield or were supplied with fodder raised elsewhere. $\delta^{13}C$ values from these same samples in the teeth of sheep and goats exhibit considerable intra-individual variation suggesting of a seasonally variable diet incorporating significant wild forage while uniformly higher values in the teeth of cattle suggest that they consumed mostly agricultural produce throughout the year. $\delta^{18}O$ values in the teeth of both sets of domestic livestock exhibit considerable intra-individual variation commensurate with the seasonal variation in temperature and rainfall characteristic of the region while variation between taxa is consistent with observed dietary differences. Taken together, our findings provide new information regarding the ways in which the domestic animals consumed at Bagasra were raised and obtained while establishing an empirical baseline necessary for further exploration of the land-use changes that may have accompanied the emergence and decline of South Asia's first urban civilization.

1. Introduction

The Indus Civilization (2600–1900 BC) in Gujarat is characterized by a series of small yet monumentally walled settlements located along trade and travel corridors (Ajithprasad and Sonawane, 2011; Bhan, 1994; Possehl, 1992; Sonawane, 2005). The manufacture and use of typically Harappan material culture at these settlements demonstrates that many residents of these sites participated in exchange and interaction networks that linked them to distant Indus cities. Less is known, however, regarding the ways in which they were situated into their local landscapes. Archaeological faunal remains represent a direct interface between human societies and their physical environments and thus have the potential to provide powerful insights into these issues. Here, analyses of faunal remains from Bagasra, one such small walled manufacturing settlement are combined with an initial consideration of biogenic isotopes of strontium, carbon, and oxygen in the tooth enamel of domestic animals to explore issues of animal mobility and diet at this important Harappan settlement. Our findings provide new information regarding the ways in which the domestic animals consumed at Bagasra were raised and obtained by its residents, establishing an empirical baseline necessary for further exploration of the land-use changes that may have accompanied the emergence and decline of South Asia's first state-level society.

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2. Background

The incorporation of the modern Indian state of Gujarat into the trade and interaction networks that linked its residents to the distant cities of Harappa and Mohenjodaro is a defining characteristic of the Integration Era of the Indus Civilization (2600–1900 BC) (Kenoyer, 1998; Possehl, 2002; Wright, 2010) (Fig. 1). Comprised of the large island of Kutch, the peninsula of Saurashtra (likely an island during Indus times), and the plains of the mainland, Gujarat lies outside the alluvium of the Indus and Ghaggar-Hakra river systems where many of the characteristic elements of Indus material culture and social practice developed during the fourth and early third millennia BC (Kenoyer, 1991a; Mughal, 1992). Preceding this period of integration, the regions of Gujarat were occupied by foraging and pastoral communities residing in small, architecturally ephemeral settlements situated along seasonal drainages and monsoonal waterholes who used microlithic tools and developed a variety of regional ceramic styles (Ajithprasad, 2002, 2011; Possehl, 2007). While ceramics similar to those produced in Sindh are known from several of these earlier sites, the interaction between the residents of Gujarat and the Indus alluvium appear to have been sporadic.

With the emergence of fully developed urban centers, such as Mohenjodaro and Harappa in Sindh and the Punjab, respectively,

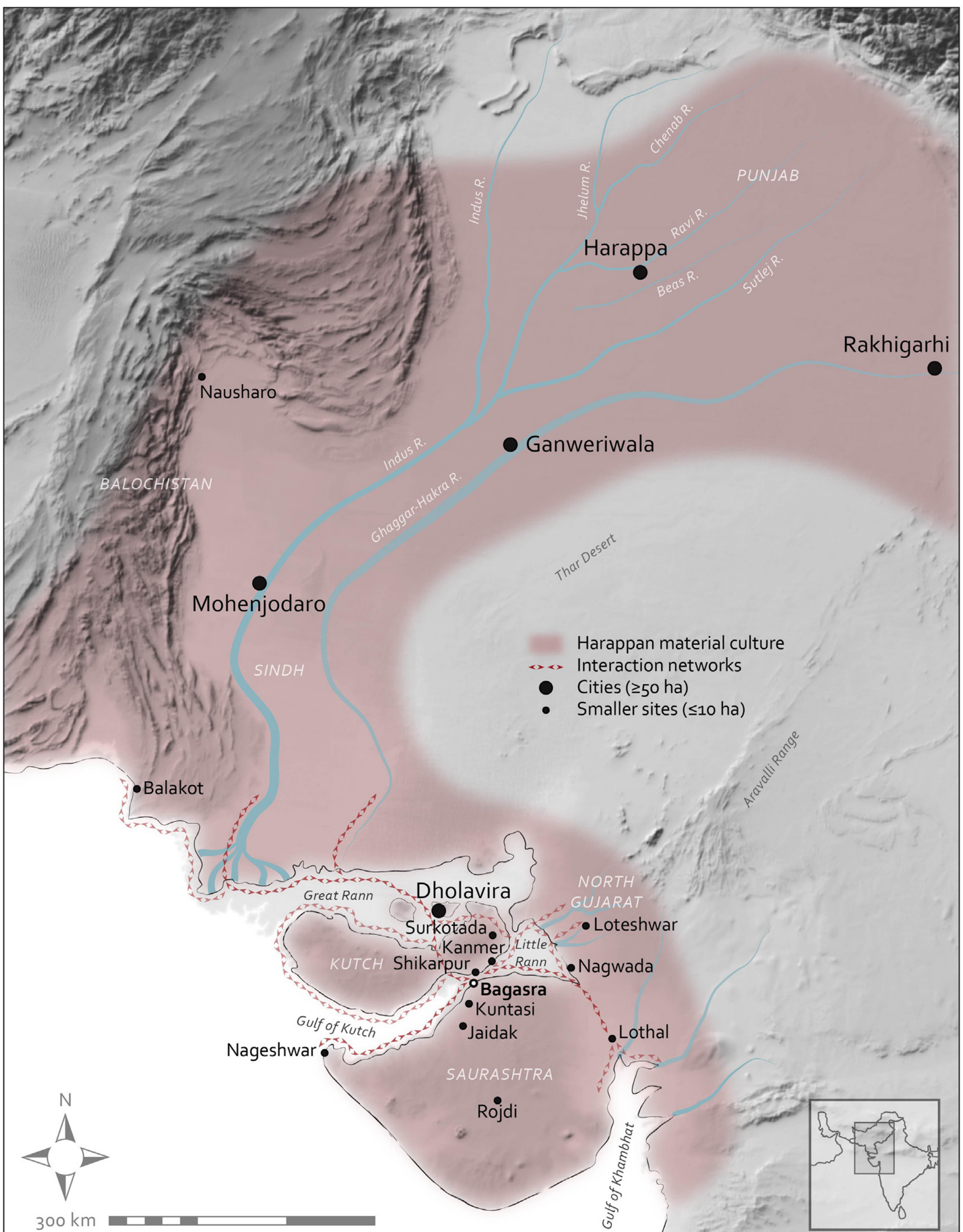


Fig. 1. A map of the Indus Civilization highlighting Bagasra and other sites mentioned in the text.

and the establishment of the planned city of Dholavira in Kutch around 2600 BC, elements of typically Harappan material culture came to be used at a series of small settlements throughout Gujarat (Ajithprasad and Sonawane, 2011; Possehl, 1992; Sonawane, 2005). Although most are only a few hectares in areal extent, massive stone or mudbrick walls, often constructed of bricks in the same proportions as those used in the Indus cities, surround many. In addition to local ceramic styles characteristic of earlier settlements in Gujarat, the residents of these settlements also used highly distinctive classical Harappan ceramic types as known from Harappa and Mohenjodaro. In addition to Harappan ceramics, the residents of these settlements used a wide range of Harappan material culture including programmatically standardized steatite seals featuring the Indus script, newly developed Harappan bead and bangle styles, and characteristically Harappan terracotta craft objects. Beyond consumption of Harappan objects, the residents of these settlements were often intensely involved in the manufacture of Harappan style ornaments from locally available raw materials such as marine shell bangles and hard stone beads that are distributed at sites large and small throughout the wider Indus Civilization (Bhan et al., 2002; Kenoyer, 1997; Vidale, 2000). Contemporaneous with these settlements are numerous largely ephemeral, mostly inland settlements where exclusively local ceramic styles were in use and where typically Harappan material culture is rare or absent (Ajithprasad and Sonawane, 2011; Possehl, 1992; Sonawane, 2005). The social processes that integrated the residents of these various types of sites into the wider Indus Civilization require further investigation. Nevertheless, it is clear that the residents of the walled Indus settlements participated in long-distance interaction networks through which goods, ideas, and people passed into—and out from—this socially dynamic borderland zone (Chase et al., 2014). Much less is known, however, about how they were situated into their *local* physical and social landscapes.

Exploration of this issue is of critical importance for understanding the economic and social dynamics of South Asia's first urban civilization. For example, it is presently unclear the extent to which the residents of small, walled Harappan settlements in Gujarat were supplied with subsistence goods produced by non-residents. It is possible that the residents themselves produced the some or all of the food consumed at these settlements. Alternatively, as specialist traders and craftspeople, they may have obtained some or all of their food from non-resident producers, perhaps the residents of the many contemporaneous inland settlements. Each of these scenarios respectively suggests a very different set of economic and social dynamics accompanying the incorporation of Gujarat into the wider Indus Civilization. In the former, the residents of the small, walled settlements would have been largely self-sufficient in terms of the subsistence goods necessary for the maintenance of their lifestyle, suggesting economic and social insularity *vis-à-vis* their neighbors. In the latter, their livelihoods would have been dependent upon not only food produced by others but also the economic and social networks through which they interacted with non-resident food producers. As we show below, however, there is good reason to believe that these models are not mutually exclusive; different products were produced or procured in different ways. Moreover, it is quite possible that these patterns of economic and social interaction changed considerably from the establishment of these settlements to their eventual abandonment at the end of the Integration Era. Indeed, understanding changes in the organization of this crucial aspect of daily life will provide a new source of information regarding the economic and social processes that accompanied the emergence and decline of the Indus Civilization in Gujarat. The remains of livestock consumed as food are an ideal source of information in this regard.

In life, livestock are a direct interface between humans and their physical environments that may be raised in a variety of ways, with different modes of production suggesting very different practices of land-use and social networking. In terms of geographic *mobility*, for example, cattle, buffalo, sheep, and goats may be raised in close proximity to the consuming community and be fed exclusively on locally available food and water. In this case of local production, the consuming community may indeed be largely self-sufficient in terms of their procurement of animals and pastoral products. Alternatively, animals may be led on long distance migrations to provide the herd with seasonally available food and water resources located far away from the consuming community. In these cases, procurement may be dependent upon interaction and exchange between socially distinct producing and consuming communities. In terms of *diet*, livestock may be foddered with agricultural produce or grazed on wild vegetation. These key variables of mobility and diet may be combined in various ways ranging from locally raised animals foddered on agricultural produce to long-distance migratory pastoralism in which animals are grazed exclusively on wild grasses. Other possible combinations include grazing herds on locally available wild grasses, foddering animals with agricultural produce during the course of long-distance migrations, or local production of animals in one location followed by consumption elsewhere. All of these modes of husbandry and their associated practices of land-use and social networking have been practiced by pastoral communities in various regions of modern and historic South Asia (e.g., case studies presented in Agrawal and Saberwal, 2004; Leshnik and Sontheimer, 1975; Rao and Casimir, 2003). In death, the remains of domestic animals consumed as food are among the most ubiquitous objects found at Harappan sites in Gujarat. Below we combine traditional faunal analyses with a study of biogenic isotopes in tooth enamel to explore these variables of mobility and diet to reconstruct the ways in which different classes of domestic livestock were produced at the small, walled settlement of Bagasra.

Analysis of strontium isotopes ($^{87}Sr/^{86}Sr$) in tooth enamel is ideally suited to addressing the issue of animal *mobility*. The $^{87}Sr/^{86}Sr$ ratio in the environment varies across the geological landscape with variation in the age and composition of bedrock (Bentley, 2006; Faure and Powell, 1972). As strontium behaves in a chemically similar fashion to calcium, a fixed fraction of this strontium is passed from bedrock to soil to plants consumed by livestock and is ultimately incorporated into their tooth enamel. The teeth of commonly herded livestock form early in life (Hillson, 2005) and therefore preserve a record of the $^{87}Sr/^{86}Sr$ ratio of the plants eaten during the period of enamel formation. The molar teeth of domestic ruminants (e.g., goats, sheep, cattle, buffalo) form from cusp to cervix over the course of the first one to two years of life (Hillson, 2005). Analysis of multiple samples along this growth axis thus provides an intra-annual picture of isotope ratios during the period of enamel formation (Hoppe, 2004; Julien et al., 2012; Pellegrini et al., 2008; Towers et al., 2010). The comparison of these values with measurements of biologically available $^{87}Sr/^{86}Sr$ taken from plants or non-migratory animal species across a physical landscape can be used to determine the geographical areas in which animals lived during the period of enamel formation (Evans et al., 2010; Price et al., 2002; Slater et al., 2014).

The composition of bedrock across the state of Gujarat is varied, but the peninsula of Saurashtra is dominated by the Deccan Traps (Merh, 1995), a large area characterized by continental flood basalts dating to the late Cretaceous, approximately 65 million years ago (Fig. 4). There are, however, significant inclusions of a variety of igneous rock characterized by significantly higher amounts of Rb relative to basalt (Chatterjee and Bhattacharji, 2001; Sheth et al., 2012, 2011), which can be expected to display significantly

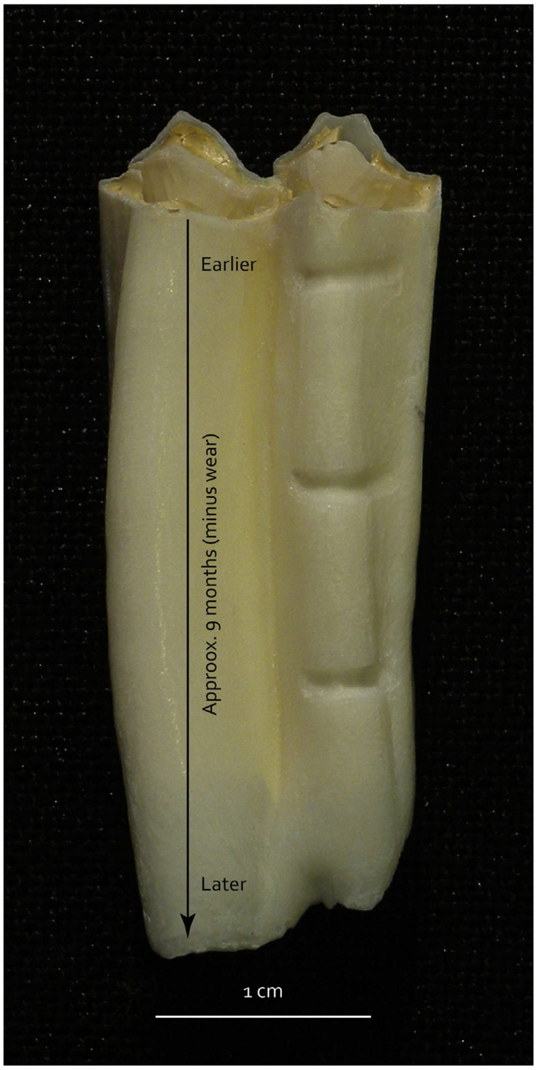


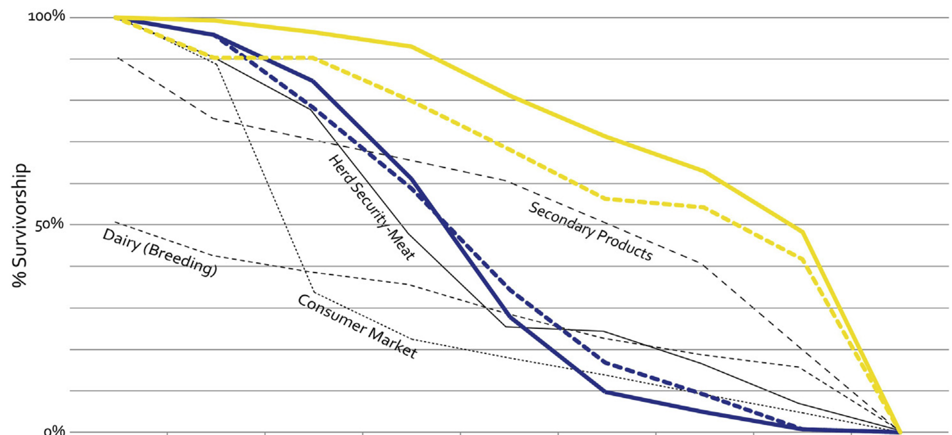
Fig. 2. A lower second molar of a goat showing sampling locations.

different $^{87}Sr/^{86}Sr$ than Deccan basalts. In the northeast of Saurashtra, there is also an area underlain by Mesozoic (Cretaceous) continental bedrock. These features suggest that geographic variation in biologically available strontium across the peninsula may be quite heterogeneous. Currently available data display large variation in strontium isotope values of volcanic rocks in Saurashtra (Peng and Mahoney, 1995; Sheth et al., 2012, 2011). Mainland Gujarat is primarily characterized by alluvium originating in the Aravalli Range, which contains significant exposures of granites and Proterozoic sedimentary rocks. The Kutch peninsula is composed of a mélange of Jurassic, Cretaceous, and Cenozoic sedimentary bedrock, as well as exposures of Deccan Trap strata. Our initial expectations, therefore, are that mainland Gujarat will display $^{87}Sr/^{86}Sr$ values generally higher than those in Saurashtra, but it is difficult to predict how biologically available strontium in Kutch may differ. The proximity of Bagasra, and other Harappan period sites, to the coast also suggests that sea spray likely contributed to biologically available values as has been documented elsewhere in the world (Herut et al., 1993; Raiber et al., 2009; Whipkey et al., 2000). In Gujarat, the process of documenting geographic variation in biologically available strontium isotope ratios is just beginning. Nevertheless, it is reasonable to posit that significant movement will be distinguishable in enamel $^{87}Sr/^{86}Sr$. It is also possible to determine whether the large and small stock consumed at Bagasra were raised nearby or elsewhere.

Analyses of carbon isotope ratios ($\delta^{13}C$) in tooth enamel is ideally suited to exploring the issue of animal *diet*. Specifically, analyses of carbon isotope ratios ($\delta^{13}C$) have addressed aspects of livestock production such as seasonal foddering, transhumance, and land use practices (Balasse, 2002; Balasse and Ambrose, 2005; Mashkour, 2003; Towers et al., 2011). Carbon isotope ratios in the terrestrial environment vary primarily due to differences in the mechanisms of photosynthesis in C_3 and C_4 plants, though variations in water availability, salinity, humidity, and density of canopy cover also contribute to specific patterns in regional plant communities (Farquhar et al., 1989; Heaton, 1999; Tieszen and Boutton, 1989). Light stable isotope ratios are conventionally expressed in the delta (δ) notation in per mil (‰) relative to a standard. $\delta^{13}C$ values in C_3 plants are significantly depleted (more negative, mean = ca. −27‰) relative to C_4 plants (mean = ca. −12‰) generally exceeding potential seasonal variation within either community. These values can be used to make inferences about the composition of past plant communities or dietary niche partitioning, particularly in wild species (Feranec, 2007; Hoppe et al., 2006). Most importantly for the purposes of the current research, carbon isotope ratios offer insight into the diets of domestic livestock animals.

Expectations for $\delta^{13}C$ values as they relate to animal diet can be drawn from ongoing archaeobotanical studies in Gujarat. Grasses and sedges represent the largest proportion of C_4 species globally, and their geographical distribution is associated with higher average annual temperatures and summer growing seasons, as opposed to C_3 species, which are predominant in areas characterized by spring growing seasons (Ehleringer et al., 1997). Archaeobotanical evidence suggests that several varieties of millets, C_4 plants, were the primary domestic cereal utilized in Gujarat during Indus times (Reddy, 1997; Weber and Kashyap, 2013; Weber et al., 2010), and so represent a key agricultural product that could have been used to fodder managed livestock. Further, analysis of modern C_3 and C_4 plants from the region (Lancelotti et al., 2013; Reddy, 1994) provides a preliminary baseline $\delta^{13}C$ for these two plant communities. While it can be expected that an animal freely grazing on wild vegetation in Gujarat may incorporate some C_4 plants into its diet, these species are not ubiquitous in the region, and therefore the enamel isotope signature will reflect consumption of mostly C_3 plants. In contrast, an animal foddered primarily with agricultural products, most likely millets, will have isotope signatures reflecting the consumption of mostly C_4 plants.

Analyses of oxygen isotopes ($\delta^{18}O$) in tooth enamel is ideally suited to exploring the hydrological environments within which animals were raised. Specifically, interpretations of oxygen isotopes ($\delta^{18}O$) have addressed mobility as well as the extent of inter-annual climate variation and the seasonality of animal birth (Balasse et al. 2003; Drucker et al. 2011; Henton, 2012; Kirsanow et al., 2008; Towers et al., 2011). The dominant effect of temperature-dependent fractionation involved in evaporation and precipitation regimes, including their paths across landforms, create geographic and seasonal patterns in regional values of oxygen isotopes (Dansgaard, 1964; Scholl et al. 2007). Values of skeletal tissues depend on body water composition, which are correlated with precipitation values (Bryant et al. 1996; Delgado-Huertas et al. 1995; Fricke and O'Neil, 1996; Fricke et al., 1998; Iacumin et al. 1996; Longinelli, 1984). Body water composition is also affected by physiological processes, such as responses to arid conditions (Kohn et al., 1996; Levin et al., 2006). Seasonal variation in $\delta^{18}O$ has been observed in sequentially-sampled tooth enamel of high-crowned prehistoric fauna (Balasse et al., 2003, 2012; Tornero et al., 2013). On the basis of predicted precipitation values derived from the



	A	B	C	D	E	F	G	H	I
Sheep/Goat	0-2 m	2-6 m	6-12 m	1-2 y	2-3 y	3-4 y	4-6 y	6-8 y	8-10 y
Phase 2 (n=85)	0.0	3.5	9.8	20.1	28.1	15.2	3.9	3.9	0.6
Phase 3 (n=42)	0.3	1.8	7.3	8.2	9.9	7.3	3.3	3.3	0.4
Cattle/Buffalo	0-1 m	1-8 m	8-18 m	18-30 m	30-36 m	Adult 1	Adult 2	Adult 3	Adult 4
Phase 2 (n=28)	0.3	0.3	0.8	1.0	3.2	2.7	2.4	4.1	13.4
Phase 3 (n=10)	0.0	1.0	0.1	1.0	1.2	1.2	0.2	1.2	4.2

Sheep/Goat Phase 2
Sheep/Goat Phase 3
Cattle/Buffalo Phase 2
Cattle/Buffalo Phase 3

Fig. 3. Mortality profiles by phase. Mandibular wear stage definitions for sheep and goats are from Payne (1973) and those for cattle and buffalo are from Halstead (1985). Milk and secondary products profiles are taken from Payne (1973), meat from Redding (1981), and market from Chase (2005). Only independent specimens are included in these analyses. Mandibles or teeth not attributable to a single stage have been proportionately assigned to stages evenly, following Zeder (1991), contra Payne (1973).

United Nations Regionalized Cluster-based Water Isotope Prediction (RCWIP) Model as a proxy (IAEA, 2o12; Terzer et al., 2013), it is anticipated that monsoon climate in Gujarat will create seasonal variability in $\delta^{18}O$ values recorded in archaeological fauna. The position of maximum $\delta^{18}O$ values in enamel profiles identifies the hottest/driest time of the year, which in Gujarat is April–June. Variation between individuals in the location of this maximum, i.e., differences in the shape of the isotope tooth profile may indicate differences in birth season, suggesting human manipulation of their animals' life cycle (e.g., Balasse et al., 2003; Towers et al., 2011).

3. Archaeological context

Bagasra[1] is an ideal site at which to explore the pastoral land-use practices of Harappan Gujarat. Excavated from 1995 to 2005 by archaeologists from the Maharaja Sayajirao University of Baroda, Bagasra is an approximately 2 ha mound with up to 7.5 m of stratified cultural material located on the northern coast of Saurashtra (Bhan et al., 2004, 2005; Sonawane et al., 2003). Established around 2500 BC during *Phase 1*, the residents of the settlement primarily used distinctively local handmade Anarta style ceramics, although items of Harappan material culture, including ceramics, were present. Shortly thereafter, *Phase 2* is defined by the building of an approximately square 65 × 57 m enclosure with walls nearly 8 m thick at their base (after three renovations), constructed of mudbricks in the typically Harappan proportion of 1:2:4 set upon a dressed stone foundation. While Anarta ceramics continued to be used, classical Harappan ceramics as known from Harappa and Mohenjodaro are predominant during this phase. Within the walls, there is considerable evidence for residents' involvement in sophisticated craft activities including the faience and stone bead industries. Most notably, Bagasra was home to a workshop dedicated to the mass production of distinctively Harappan-style shell bangles, one of the most economically and ideologically important Harappan ornaments and one of the few ornaments to be buried with the dead, mostly women, at cemeteries at Harappa (Dales and Kenoyer, 1991; Kenoyer, 1991b) and other Indus sites in the Punjab. Several steatite unicorn seals featuring the Indus script and cubical chert weights found in Phase 2 contexts are further indicative that the residents the long-distance exchange networks of the wider Indus Civilization. While the walled enclosure and most Phase 2 infrastructure were used with no stratigraphic break, *Phase 3* is nevertheless marked by a decline in crafting activities. Although distinctively local ceramics of the Sorath Harappan tradition predominate during this phase, classically Harappan ceramics continued to be used at the site. Based upon radiocarbon dates and

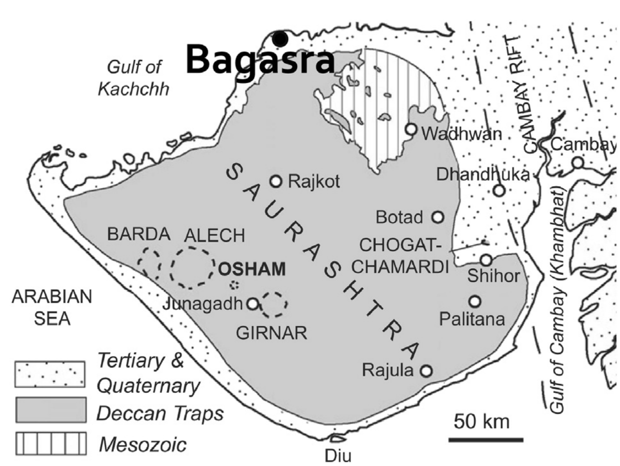


Fig. 4. The geology of Saurashtra and North Gujarat indicating the location of Bagasra (modified from Sheth et al., 2012, Fig. 1b).

[1] The archaeological site referred to here as Bagasra, the name of the nearest modern village, is also known as Gola Dhoro, the local name of the mound. Initially referred to in the literature as Bagasra (Sonawane et al., 2003), it has been referred to in subsequent publications as Gola Dhoro (Bhan et al., 2004, 2005; Chase, 2010). Here, we maintain convention and refer to it as Bagasra.

comparisons with other Harappan sites in the region, the transition to Phase 3 likely took place towards latter portion of the Integration Era around 2100 BC. By 1900 BC, during *Phase 4*, the presence of thin layers of habitation debris overlaying the walled enclosure and pits dug into earlier layers indicates that the site no longer functioned as it once had. Bagasra was likely abandoned by around 1700 BC.

4. Materials and methods

The samples under consideration here derive from 75 excavation contexts belonging to Phases 2 and 3 distributed throughout the occupational area of the site (Table 1). Most of these are primarily comprised of domestic waste and construction fill resulting from several hundred years of routine maintenance and construction activities characteristic of mounded settlements where mudbricks were the primary construction material (Friesem et al., 2014; Rosen, 1986). The faunal remains from these contexts have been documented and interpreted following methods and procedures presented in detail elsewhere (Chase, 2010). Here we focus primarily on a subset of these faunal materials, primarily the mandibles and some loose teeth of the herded domestic animals that comprise approximately 85% of the identified mammalian specimens. Below, these are used to construct *mortality profiles* showing the proportion of animals slaughtered at a range of age stages, which are below interpreted to infer the utilization priorities of their producers and consumers (e.g., meat or secondary products).

As a pilot study exploring the utility of intra-annual sampling of biogenic isotopes in this region, sheep/goat and cattle/buffalo teeth were selected for sampling from Phases 2 and 3 at Bagasra. Teeth were selected for inclusion if a) enamel on at least one surface was intact from cusp to cervix, and b) its state of preservation was such that it could withstand cleaning and sampling. Lower third molars were preferentially sampled, although as shown in Table 1, several lower second molars and upper molars were included as well. All teeth derive from independent individuals. Teeth were mechanically cleaned using carbide burrs in a dental micromotor, and rinsed in an ultrasonic bath with deionized water prior to sampling. Then, approximately 5 mg samples of powdered enamel were taken in sequential bands transverse to the enamel growth axis using a diamond bit (Fig. 2). On most teeth, three samples equally spaced from cusp to cervix were taken; on a few, more samples were taken to investigate variation at a higher resolution over the growth period of the tooth.

Enamel is laid down progressively from cusp to cervix over a defined period in life, and is not biologically modified thereafter (Hillson, 2005). Enamel formation for the second (M2) and third (M3) molars in caprines and cattle occurs approximately over the first and second years of life, respectively (Brown et al., 1960; Milhaud and Nezit, 1991; Weinrab and Sharav, 1964). Its formation occurs in a complex multi-stage series of cellular activities (Smith, 1998), however, that have significant implications for the interpretation of biogenic isotope data (Tafforeau et al. 2007). Amelogenesis can be broadly divided into two phases: matrix formation and maturation (Robinson et al., 1995; Sakae and Hirai, 1982; Smith, 1998; Suga, 1979). The relatively low mineral content of matrix enamel is dramatically increased during maturation, which comprises the bulk of the overall period of enamel formation for a particular tooth (Sakae and Hirai, 1982; Suga, 1982). These stages of cellular activity occur progressively down the tooth as enamel grows to its maximum cervical extent (Balasse et al., 2012; Kohn and Cerling, 2002; Passey and Cerling, 2002; Robinson et al., 1995). Mineral content through the width of enamel at any given point reflects body composition spanning the duration of these processes along diagonally oriented growth zones (Kierdorf et al. 2013; Moss-Salentijn et al., 1997; Smith, 2006; Zazzo et al., 2005). The sum effect of these factors is that enamel composition through its width reflects an amalgam of input values over a period of several months (Balasse et al., 2012; Zazzo et al., 2010), and not a discrete moment in the life of the animal (although for input signal fidelity of innermost enamel, see Blumenthal et al., 2014; Tafforeau et al., 2007; Zazzo et al. 2012). In this way, series of sequential transverse samples preserve a record of incremental changes in an ‘average’ of signal inputs that can be interpreted over the intra-annual scale of enamel formation (Balasse, 2002, 2003).

This pilot study initially focused primarily on analyses of strontium isotopes ($^{87}Sr/^{86}Sr$), which as discussed below, can be used to infer geographic mobility (Bentley and Knipper, 2005; Montgomery et al., 2010). For those teeth for which sufficient sample remained after analysis of strontium isotopes, this was subjected to further analyses of light isotopes, of which carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) are used below to explore aspects of animals' diet and the environmental conditions within which they lived.

Enamel samples were prepared for strontium isotope analysis according to established methods (cf. Bentley, 2006), including chromatographic purification using strontium-selective resin (Eichrom®). The aqueous strontium fraction was analyzed for $^{87}Sr/^{86}Sr$ using a multi-collector ICP-MS (Nu Plasma) equipped with a desolvating nebulizer system located in the in the Department of Geology at the University of Illinois at Urbana-Champaign. Linear normalization of sample results was applied based on within-run trends in SRM 987 relative to its accepted value (0.710255). Internal precision on repeated standard measurements was ±0.00002.

Analysis of carbon and oxygen samples in this study was carried out at the University of Illinois at Urbana-Champaign according to established procedures (Balasse and Ambrose, 2005), with samples placed in 2–3% hypochlorite solution to remove organic contaminants and 0.1 M acetic acid to remove labile diagenetic carbonate. After each step samples were washed three times with ultra-pure water, and freeze-dried after the final rinse. Dry samples were loaded onto a Kiel device in which CO_2 is liberated from enamel by reaction with 90 °C phosphoric, cryogenically distilled, and subsequently flows to a Finnigan MAT 252 mass spectrometer operated in dual-inlet mode. Analytical precision is typically ±0.1‰ for $\delta^{13}C$ and 0.2‰ for $\delta^{18}O$ (see below). The value $\delta^{13}C$ in animal tissues reflects dietary input, with differences between values in consumed plants and skeletal tissues arising from fractionation during physiological processes (Ambrose and Norr, 1993; Schwarcz, 2000). Of particular note, $\delta^{13}C$ in skeletal tissues of ruminant herbivores are enriched ca. 10–14‰ relative to their diet due their digestive physiology (Bocherens, 2000).

5. Data and interpretations

As discussed in detail elsewhere (Chase, 2010), herded domestic animals, sheep/goat and cattle/buffalo comprise approximately 85% of the assemblage of identified mammalian specimens from the studied contexts, with the bones of pigs comprising up to 10%, mostly from contexts inside the walled enclosure. In both phases, the ratio of specimens identified as cattle (*Bos sp.*) or buffalo (*Bubalus bubalis*) to those identified as goat (*Capra hircus*) or sheep (*Ovis aries*) specimens is approximately 1.5:1. The problem of distinguishing fragmentary bones (e.g., Boessneck, 1969; Prummel and Frisch, 1986; Zeder and Lapham, 2010) and teeth (e.g., Halstead et al., 2002; Payne, 1985; Zeder and Pilaar, 2010) of goats and sheep is notoriously difficult and continues to generate considerable research and debate. Among those specimens that have been identified to the species level, goat specimens predominate over sheep 2:1. The literature regarding the distinction of

Table 1
Tooth enamel samples from Bagasra included in the present study. Specimen# refers to the number given to a particular tooth during faunal analyses. In the Tooth field, L/U indicates upper/lower and M1-3 indicates tooth position (e.g., LM1 denotes a lower first molar).

Specimen#	Phase	Taxon	Tooth	Distance from cervix (mm)	$^{87}Sr/^{86}Sr$	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (SMOW)
Ea12-100	2	Goat	LM2	18.9	0.7093		
Ea12-100	2	Goat	LM2	11.7	0.7093		
Ea12-100	2	Goat	LM2	3.5	0.7093		
Ea12-160	2	Cattle/Buffalo	LM3	33.9	0.7092	3.39	32.92
Ea12-160	2	Cattle/Buffalo	LM3	20.9	0.7093	2.73	35.04
Ea12-160	2	Cattle/Buffalo	LM3	6.6	0.7092	2.79	34.69
Ea12-228	2	Cattle/Buffalo	LM3	34.2	0.7087		
Ea12-228	2	Cattle/Buffalo	LM3	21.4	0.7087		
Ea12-228	2	Cattle/Buffalo	LM3	21.4	0.7087		
Ea12-228	2	Cattle/Buffalo	LM3	8.2	0.7087		
Eb10-67	2	Sheep/Goat	LM3	24.6	0.7093	−1.18	35.68
Eb10-67	2	Sheep/Goat	LM3	21.6	0.7093	−0.31	34.27
Eb10-67	2	Sheep/Goat	LM3	11.4	0.7093	−0.32	33.94
Eb10-67	2	Sheep/Goat	LM3	3.6	0.7093		
Eb13-25	2	Cattle/Buffalo	LM3	25.2	0.7094		
Eb13-25	2	Cattle/Buffalo	LM3	15.6	0.7094		
Eb13-25	2	Cattle/Buffalo	LM3	3.9	0.7094		
Eo2-623	2	Cattle/Buffalo	LM3	41.7	0.7093		
Eo2-623	2	Cattle/Buffalo	LM3	26.2	0.7093		
Eo2-623	2	Cattle/Buffalo	LM3	7.7	0.7093		
Eo2-665	2	Goat	LM1	25.9	0.7094		
Eo2-665	2	Goat	LM1	16.1	0.7094		
Eo2-665	2	Goat	LM1	5.9	0.7094		
Eo2-705	2	Cattle/Buffalo	LM3	50.0	0.7090		
Eo2-705	2	Cattle/Buffalo	LM3	30.7	0.7091		
Eo2-705	2	Cattle/Buffalo	LM3	9.5	0.7092		
Eo2-765	2	Cattle/Buffalo	LM3	32.3	0.7098	3.81	32.15
Eo2-765	2	Cattle/Buffalo	LM3	20.6	0.7098	2.96	32.03
Eo2-765	2	Cattle/Buffalo	LM3	5.3	0.7099	2.49	32.34
Eo2/Eo6-827	2	Goat	LM2	23.6	0.7093	−6.61	37.22
Eo2/Eo6-827	2	Goat	LM2	14.3	0.7093	−5.72	39.21
Eo2/Eo6-827	2	Goat	LM2	5.1	0.7093	−4.51	35.66
Eo2/Eo6-837	2	Goat	LM2	21.9	0.7091		
Eo2/Eo6-837	2	Goat	LM2	11.5	0.7091		
Eo2/Eo6-837	2	Goat	LM2	3.0	0.7092		
Eo6-6831	2	Goat	LM2	27.6	0.7093		
Eo6-6831	2	Goat	LM2	17.5	0.7093		
Eo6-6831	2	Goat	LM2	7.5	0.7093		
Eo6-692	2	Goat	LM1	24.6	0.7093		
Eo6-692	2	Goat	LM1	18.1	0.7093		
Eo6-692	2	Goat	LM1	7.5	0.7093		
Eo6-768	2	Sheep/Goat	LM2	25.5	0.7093		
Eo6-768	2	Sheep/Goat	LM2	14.4	0.7093		
Eo6-768	2	Sheep/Goat	LM2	8.1	0.7093		
Eo6-813	2	Cattle/Buffalo	LM3	31.6	0.7094		
Eo6-813	2	Cattle/Buffalo	LM3	18.9	0.7094		
Eo6-813	2	Cattle/Buffalo	LM3	6.7	0.7094		
Eq2-251	2	Sheep/Goat	LM1/2	26.3	0.7092		
Eq2-251	2	Sheep/Goat	LM1/2	15.1	0.7093		
Eq2-251	2	Sheep/Goat	LM1/2	7.2	0.7092		
Eq2-369	2	Cattle/Buffalo	LM3	32.3	0.7093	2.70	33.04
Eq2-369	2	Cattle/Buffalo	LM3	27.5	0.7093	2.58	33.65
Eq2-369	2	Cattle/Buffalo	LM3	23.1	0.7094	2.61	34.27
Eq2-369	2	Cattle/Buffalo	LM3	19.5		2.65	34.47
Eq2-369	2	Cattle/Buffalo	LM3	16.5		2.68	34.84
Eq2-369	2	Cattle/Buffalo	LM3	12.5		2.78	34.83
Eq2-369	2	Cattle/Buffalo	LM3	9.2		2.74	32.93
Eq2-369	2	Cattle/Buffalo	LM3	6.2		2.63	31.84
Eq2-398	2	Goat	LM2	29.2	0.7092		
Eq2-398	2	Goat	LM2	19.4	0.7092		
Eq2-398	2	Goat	LM2	10.8	0.7092		
Eq2-399	2	Goat	LM3	26.6	0.7092		
Eq2-399	2	Goat	LM3	16.2	0.7092		
Eq2-399	2	Goat	LM3	8.6	0.7092		
Eq2-481	2	Sheep/Goat	LM2	24.5	0.7091		
Eq2-481	2	Sheep/Goat	LM2	15.8	0.7091		
Eq2-481	2	Sheep/Goat	LM2	7.2	0.7092		
Ek5-1	3	Sheep/Goat	LM1/2	33.0	0.7093		
Ek5-1	3	Sheep/Goat	LM1/2	19.3	0.7093		
Ek5-1	3	Sheep/Goat	LM1/2	8.7	0.7093		
Ek5-115	3	Sheep/Goat	UM1/2	20.5	0.7094		
Ek5-115	3	Sheep/Goat	UM1/2	13.7	0.7094		

(*continued on next page*)

Table 1 (*continued*)

Specimen#	Phase	Taxon	Tooth	Distance from cervix (mm)	$^{87}Sr/^{86}Sr$	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (SMOW)
Ek5-115	3	Sheep/Goat	UM1/2	6.2	0.7094		
Ek5-167	3	Cattle/Buffalo	LM3	34.0	0.7088	3.09	33.04
Ek5-167	3	Cattle/Buffalo	LM3	20.6	0.7089	2.76	32.09
Ek5-167	3	Cattle/Buffalo	LM3	6.7	0.7089	2.85	31.55
Ek5-177	3	Cattle/Buffalo	LM3	48.6	0.7098		
Ek5-177	3	Cattle/Buffalo	LM3	28.5	0.7097		
Ek5-177	3	Cattle/Buffalo	LM3	11.3	0.7094		
Ek5-317	3	Goat	LM1/2	23.0	0.7099		
Ek5-317	3	Goat	LM1/2	14.5	0.7099		
Ek5-317	3	Goat	LM1/2	4.0	0.7098		
Ek5-389	3	Sheep/Goat	LM3	29.3	0.7094		
Ek5-389	3	Sheep/Goat	LM3	19.9	0.7094		
Ek5-389	3	Sheep/Goat	LM3	9.8	0.7094		
Ek5-415	3	Cattle/Buffalo	LM3	21.0	0.7092	2.74	32.83
Ek5-415	3	Cattle/Buffalo	LM3	13.0	0.7092	3.51	33.30
Ek5-415	3	Cattle/Buffalo	LM3	4.2	0.7091	3.73	32.36
Ek5-479	3	Sheep/Goat	UM2	19.5	0.7094	−7.18	37.38
Ek5-479	3	Sheep/Goat	UM2	13.0	0.7093	−6.09	37.37
Ek5-479	3	Sheep/Goat	UM2	5.2	0.7093	−6.96	33.09
Ek5-480	3	Sheep/Goat	UM3	26.2	0.7094		
Ek5-480	3	Sheep/Goat	UM3	16.5	0.7094		
Ek5-480	3	Sheep/Goat	UM3	5.6	0.7094		
Ek5-534	3	Cattle/Buffalo	UM2	41.6	0.7096	2.45	32.69
Ek5-534	3	Cattle/Buffalo	UM2	22.6	0.7097	1.78	32.98
Ek5-534	3	Cattle/Buffalo	UM2	5.0	0.7096	2.85	35.51
Eo2-116	3	Goat	LM2	24.4	0.7094		
Eo2-116	3	Goat	LM2	15.6	0.7094		
Eo2-116	3	Goat	LM2	5.6	0.7094		
Eo2-137	3	Cattle/Buffalo	LM3	41.0	0.7095	3.40	35.12
Eo2-137	3	Cattle/Buffalo	LM3	26.4	0.7095	3.48	32.47
Eo2-137	3	Cattle/Buffalo	LM3	6.7	0.7095		
Eo2-137	3	Cattle/Buffalo	LM3	6.7	0.7095		
Eo2-163	3	Sheep/Goat	LM2	32.2	0.7092		
Eo2-163	3	Sheep/Goat	LM2	32.1		1.83	34.29
Eo2-163	3	Sheep/Goat	LM2	28.5		1.26	35.28
Eo2-163	3	Sheep/Goat	LM2	25.2		0.54	36.77
Eo2-163	3	Sheep/Goat	LM2	21.7		−0.01	37.78
Eo2-163	3	Sheep/Goat	LM2	21.0	0.7093		
Eo2-163	3	Sheep/Goat	LM2	17.9		−0.13	38.25
Eo2-163	3	Sheep/Goat	LM2	14.6		0.21	37.89
Eo2-163	3	Sheep/Goat	LM2	11.2		0.93	36.44
Eo2-163	3	Sheep/Goat	LM2	9.3	0.7092		
Eo2-175	3	Cattle/Buffalo	LM3	29.4	0.7093		
Eo2-175	3	Cattle/Buffalo	LM3	15.5	0.7093		
Eo2-175	3	Cattle/Buffalo	LM3	5.4	0.7093		
Eo2-197	3	Goat	LM2	22.5	0.7093		
Eo2-197	3	Goat	LM2	13.6	0.7093		
Eo2-197	3	Goat	LM2	5.6	0.7093		
Eo2-293	3	Sheep/Goat	LM2	19.5	0.7094		
Eo2-293	3	Sheep/Goat	LM2	11.4	0.7094		
Eo2-293	3	Sheep/Goat	LM2	4.0	0.7094		
Eo2-309	3	Cattle/Buffalo	LM3	38.6	0.7093	3.21	35.58
Eo2-309	3	Cattle/Buffalo	LM3	23.5	0.7093	3.78	33.80
Eo2-309	3	Cattle/Buffalo	LM3	7.6	0.7093	3.05	36.16
Eo2-376	3	Sheep/Goat	LM2	25.3	0.7093		
Eo2-376	3	Sheep/Goat	LM2	15.5	0.7093		
Eo2-376	3	Sheep/Goat	LM2	6.6	0.7093		
Eo2-96	3	Goat	LM2	24.9	0.7093		
Eo2-96	3	Goat	LM2	24.5	0.7093		
Eo2-96	3	Goat	LM2	15.8	0.7093		
Eo2-96	3	Goat	LM2	15.6	0.7093		
Eo2-96	3	Goat	LM2	5.3	0.7093		
Eo2-96	3	Goat	LM2	4.4	0.7093		
BSR 00		Pig			0.7093		
BSR 01		Pig			0.7101		
BSR 02		Pig			0.7093		
BSR 03		Pig			0.7093		

cattle from buffalo is less well developed. Nevertheless, based upon preliminary identifications (following Meadow, 1981), it appears that the remains of cattle predominate over buffalo by approximately 2:1. Given these considerations, in most of the analyses below goats and sheep are considered as a single analytic category, as are cattle and buffalo. There is evidence for some movement of prepared meat from goats and sheep with limb portions more common inside the walls during Phases 2 and 3 (Chase, 2010, 2012).

This is not the case for cattle and buffalo, all skeletal portions of which are uniformly distributed throughout the settlement. Here, we focus primarily on the mortality profiles of the herded domestic animals.

5.1. Mortality profiles

The mortality profiles shown in Fig. 3 demonstrate that goats and sheep were raised in very different ways than were cattle and buffalo. Specifically, goats and sheep were most often slaughtered in their second and third year as they approached their maximum weight with only 10–20% living beyond this age. This slaughter pattern for small stock matches Redding's (1984) herding model in which animals are raised principally for the production of primary products, i.e., meat, in a way that ensures herd security through the maintenance of breeding stock. Cattle on the other hand regularly lived until full adulthood and beyond. This slaughter pattern indicates that the larger stock had been kept primarily for secondary products such as milk and traction prior to being consumed by the residents of Bagasra. This pattern contrasts with Payne's (1973) hypothetical model of specialized dairy production in that there is no evidence for the routine slaughter of young male calves; rather *most* cattle were slaughtered late in life. This may be the result of either keeping bulls and bullocks for traction alongside cows for milk or perhaps the import of milk cattle initially raised elsewhere. Unfortunately, the present state of knowledge regarding species distinctions among the large stock and breed variation within these preclude the morphometric analyses required to distinguish cow, bulls, and castrates among the cattle and buffalo. Despite these uncertainties, it is clear that the goats and sheep eaten at Bagasra were primarily raised for meat while cattle and buffalo were raised primarily for secondary products. It is not clear however, *where*—or by whom—these animals were raised. Did the residents of Bagasra raise livestock locally? Or did they obtain animals for consumption raised elsewhere, possibly by non-resident pastoral producers? We directly address these questions in the analyses of biogenic isotopes of strontium, carbon, and oxygen that follow.

5.2. Strontium isotopes

The $^{87}Sr/^{86}Sr$ ratios presented in Fig. 5 show significant differences in the mobility regimes experienced by goats and sheep as compared to cattle and buffalo. Specifically, a relatively small degree of variation within individuals across the three samples taken from the teeth of goats and sheep suggests that most did not move across the landscape very much during the period of enamel formation. The average $^{87}Sr/^{86}Sr$ ratio among the goats and sheep during both Phases 2 and 3 is close to 0.7093. This is very close to three of four enamel samples taken from pig teeth excavated from Bagasra. Because they are rarely herded across the landscape, $^{87}Sr/^{86}Sr$ ratios in pig teeth are often taken to approximate those of the local biosphere (although in this case, one pig was almost surely raised in a different location than the others). Moreover, this average value is close to the global value for seawater, 0.7092, which is to be expected given Bagasra's coastal setting and the consequent incorporation of seawater into the local biosphere. For these reasons, we feel that the most parsimonious interpretation of these data is that most goats and sheep were raised nearby the site prior to consumption in their second or third year of life. As with the goats and sheep, most cattle and buffalo as well (with a few exceptions) show little intra-annual variation. While the average for the cattle and buffalo is likewise near 0.7093 during both Phases 2 and 3, there is considerably more variation *between* individuals than is the case for goats and sheep. Several sampled individuals have values considerably higher than those observed in presumably locally raised goats and sheep while several other individuals have considerably lower values. Taken together, these findings suggest either a) that many of the cattle and buffalo consumed at Bagasra were initially raised elsewhere prior to consumption at Bagasra or b) that they were fed with agricultural fodder that was raised elsewhere and transported to the site. At present it is not known from where or how far away the higher and lower $^{87}Sr/^{86}Sr$ ratios derive. The next phase of this project, currently in progress, involves the systematic sampling of Gujarat's considerable mineralogical variation to help refine the interpretation of these data. While these analyses potentially provide information regarding the

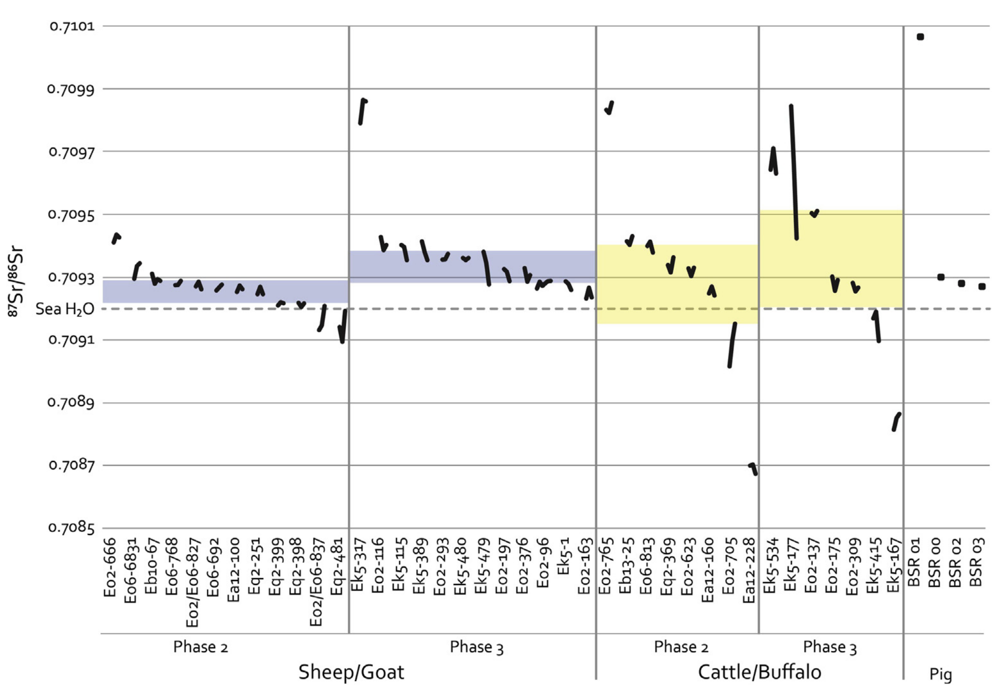


Fig. 5. $^{87}Sr/^{86}Sr$ ratios at Bagasra. Shaded areas indicate interquartile ranges by taxa and phase; lines connect the samples from an individual tooth as shown in Fig. 2.

movement of animals (or fodder) across the landscape, information regarding their diet is best explored using carbon isotopes.

5.3. Carbon isotopes

The $\delta^{13}C$ values presented in Fig. 6 show significant differences in the dietary regimes of goats and sheep as compared to cattle and buffalo. Specifically, individual goats and sheep exhibit considerable variation both within as well as between individuals. Variation in $\delta^{13}C$ values *within* individuals suggests that the composition of their diet *vis-à-vis* $C_3$and C_4 plants changed considerably during the period of enamel formation. Variation in $\delta^{13}C$ values *between* individuals suggests that while some individuals, those with the highest values, had access to mostly agricultural produce, others consumed a greater proportion of wild vegetation. The most parsimonious explanation of this pattern is that individual goats and sheep were grazed by their owners on a seasonally variable dietary regime that included both wild and agricultural products as available throughout period of enamel formation. In contrast, cattle and buffalo show very little variation either within or between individuals, suggesting a significantly more homogenous diet. The majority of $\delta^{13}C$ values suggest a diet comprised almost exclusively of agricultural produce, most likely hay of millet, a ubiquitous fodder for livestock in the region today. The low degree of variation in $\delta^{13}C$ values between individuals further demonstrates that cattle and buffalo were foddered with agricultural produce throughout the period of enamel formation, suggesting that agricultural produce was likely stored specifically for their consumption. Taken together, these finds suggest that while cattle and buffalo were ensured a steady supply of agricultural products during enamel formation in early life, the diets of goats and sheep varied throughout this period and included a significant amount of wild vegetation. While these analyses provide information regarding seasonal variation in diet, analysis of oxygen isotopes provides complementary information regarding seasonal variation in temperature and rainfall, refining these observations.

5.4. Oxygen isotopes

The $\delta^{18}O$ values presented in Fig. 7 show that all individuals of both categories of livestock experienced considerable seasonal variation in temperature and rainfall. As discussed above, this is expected in a highly seasonal environment such as Gujarat. Of interest is the preliminary observation that the shapes of the $\delta^{18}O$ curve differs between individuals more than might be expected based on inter-individual variability (c.f., Balasse et al. 2012). This is the case, for example, with lower third molar Eq2-369 and lower second molar Eo2-309, suggesting these teeth formed during different seasons (or possibly that they had different mobility regimes during these periods although the Sr data presented in Fig. 5 suggests that they experienced similar patterns of movement). This is an issue that will be investigated in more detail in the next phase of this project. While the degree of intra-individual variation is similar between small and large stock, the goats and sheep have significantly higher $\delta^{18}O$ values than do cattle and buffalo. This most likely relates to differences in their diet. As discussed above, goats predominate among the sample of small stock specimens for which species identifications have been made. Goats (and to a lesser degree sheep) often include a large proportion of leafy herbaceous plants in their diets, which generally have higher $\delta^{18}O$ values as compared to grassy plants, than do cattle or buffalo (Barbour et al., 2005; Laca et al. 2010).

While these data demonstrate that all animals experienced considerable variation in temperature and precipitation throughout the year, carbon and oxygen isotope data are best analyzed simultaneously within individuals. As part of the pilot study, a greater number of enamel samples were taken from one lower second molar of a sheep/goat (Eo2-163 in Table 1) and one individual lower third molar of a cattle/buffalo (Eq2-369 in Table 1). Fig. 8 shows that while each individual experienced generally synchronous variation in $\delta^{18}O$ values throughout the period of enamel formation, the individual small stock (an indeterminate sheep/goat) has higher values than the individual large stock. This is consistent with the data presented in Fig. 6. As higher values $\delta^{18}O$ values are characteristic of the hottest, driest time of the year (from

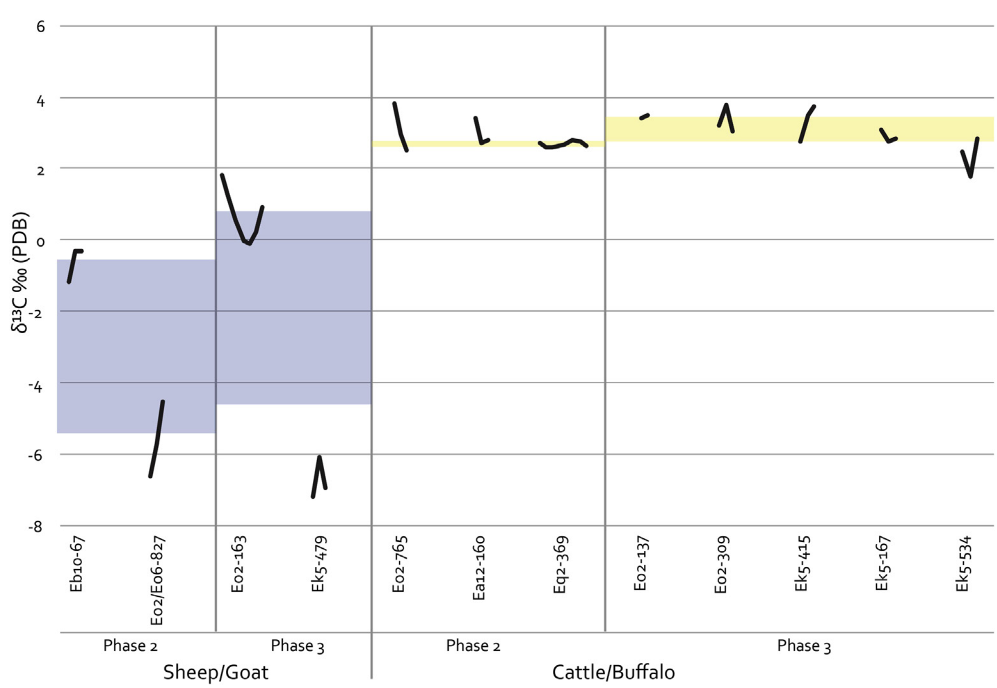


Fig. 6. $\delta^{13}C$ values at Bagasra. Shaded areas indicate interquartile ranges by taxa and phase; lines connect the samples from an individual tooth as shown in Fig. 2.

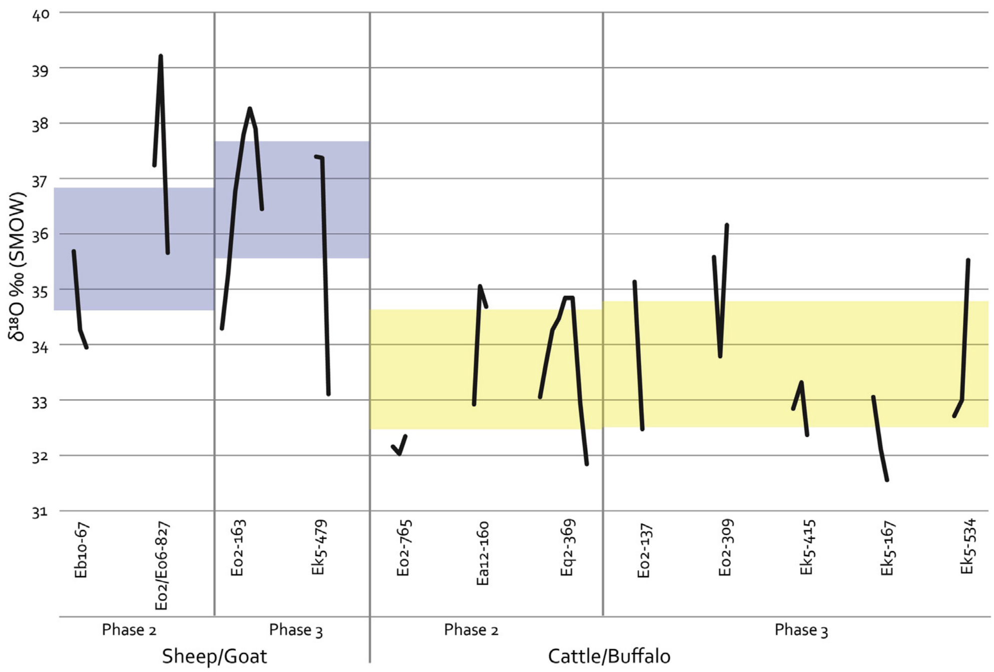


Fig. 7. $\delta^{18}O$ values at Bagasra. Shaded areas indicate interquartile ranges by taxa and phase; lines connect the samples from an individual tooth as shown in Fig. 2.

April to June in Gujarat), the isotope signal recorded during the period of enamel formation in these individuals spans this period. While both individuals experienced similar seasonal temperature changes, $\delta^{13}C$ values through this period exhibit considerable differences. Specifically, the diet of the small stock individual varied through this period with its maximum intake of agricultural C_4 foods occurring during wetter, cooler times of the year; during the hottest, driest portion of the year, this individual consumed the highest proportion of wild C_3 vegetation. A parsimonious explanation for this pattern is that as local fields of millet stalks were depleted in the dry season following the harvest, this individual was moved to nearby pastures of wild vegetation to feed. This pattern is not evident in the individual large stock, however. This individual continued to eat agricultural C_4 produce throughout the year. This pattern would result had the residents of the site had stored agricultural fodder for its consumption throughout the period of third molar formation, typically an animal's second year of life. Although we anticipate similar levels of isotope signal averaging between the two groups of species included in this study, further research is necessary to allow appropriate comparison of intra-annual dietary regimes. Currently limited to only two individuals, this pattern of seasonality and diet are generally consistent with the interpretations of $\delta^{13}C$ and $\delta^{18}O$ variation developed above.

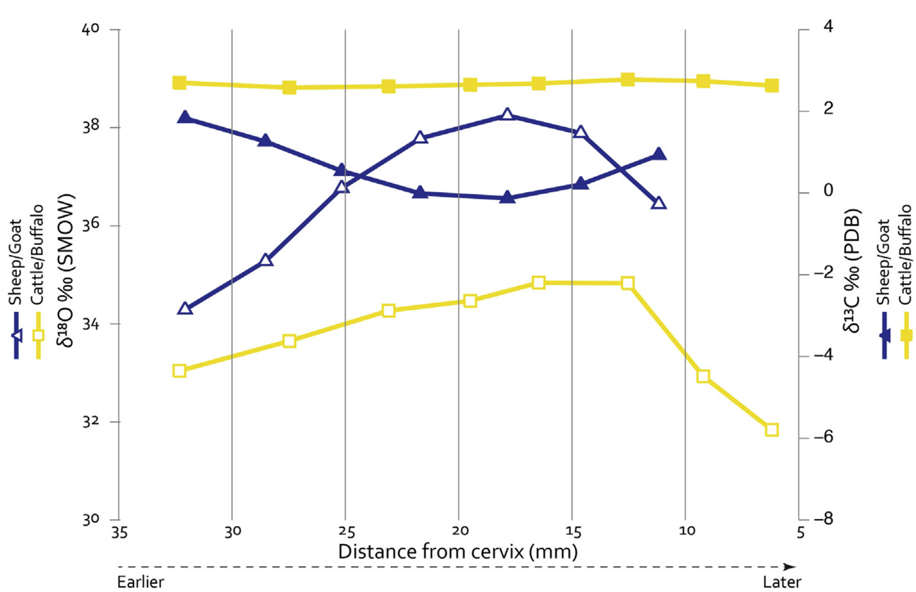


Fig. 8. Intra-annual variation in $\delta^{13}C$ and $\delta^{18}O$ in a lower second molar of a sheep/goat (Eo2-163) and lower third molar of a cattle/buffalo (Eq2-369).

6. Discussion

The data and interpretations presented above demonstrate that the small stock, goats and sheep, and large stock, cattle and buffalo, consumed at Bagasra were raised following very different mobility and dietary regimes. This is shown in Fig. 9, which includes only those individuals for which both $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ values are currently available. In general, small stock spent the period of enamel formation near to Bagasra and grazed on a seasonally variable diet consisting of both wild and agricultural food prior to slaughter upon reaching their full weight. In contrast, several of the large stock included in the study either spent the period of enamel formation further afield from the site or were foddered with agricultural products grown in these areas prior to slaughter at Bagasra towards the end of their useful life as suppliers of milk and traction.

While the residents of Bagasra were the primary producers of goats and sheep, which were grazed near the site, they were far from being self-sufficient in terms of livestock production. Rather, they appear to have been dependent upon cattle and buffalo with $^{87}Sr/^{86}Sr$ values that suggest that they either had been raised in a variety of mineralogical regions throughout the wider region or at least fed with agricultural fodder imported from these as yet unidentified areas. We are currently in the process of collecting the data necessary to refine our interpretations regarding the geographic location of these source areas. Low intra-individual variation in values, however, suggests that most large stock were not highly mobile during this period, but were rather kept in one place during the period of enamel formation, during which time they were foddered with agricultural produce. It is possible that these cattle were initially raised at or foddered with agricultural produce gown near one of the numerous contemporary settlements in Gujarat. The presence at Bagasra of both classically Harappan as well as more distinctively local material culture forms suggests economic relations with either other walled Harappan settlements, the numerous largely ephemeral settlements where Harappan material culture is absent, or both. A better understanding of the geographic variation in biologically available strontium isotope ratios across the region and the analyses of samples from other contemporaneous sites is underway and will soon allow us to address this question in more detail.

These findings suggest that the residents of Bagasra during Phases 2 and 3 depended on regular interaction with a network of pastoral producers throughout the wider region for a large portion of their subsistence needs, primarily associated with the acquisition of cattle and/or the fodder necessary for their maintenance. This is consistent with the presence of a variety of distinctively local ceramic forms at the site as noted above. As Lindstrom has discussed in relation of her study of the ceramics from the site, most of the cooking pots used by the residents of Bagasra were indeed of local ceramic styles rather than classically Harappan styles as known from Harappa and Mohenjodaro (Lindstrom, in press, 2013). While the residents of the site regularly participated in long-distance interaction networks linking them to the wider Indus Civilization beyond Gujarat, their domestic lives revolved around distinctly local cuisine practices. The interpretations of the isotopic data presented here further suggest that the residents of Bagasra were also dependent upon relationships with non-local producers for the acquisition and/or maintenance of at least some of their cattle, which, as the predominant livestock animals consumed at the site, were absolutely critical for the maintenance of their lifestyle.

This study has included individuals from both Phases 2 and 3, yet diachronic change has not been a focus of our interpretations. This is because the data at hand from these two periods currently show no clear differences. As discussed above, the transition from Phase 2 to Phase 3 was a time of considerable economic and social change at Bagasra. Craft industries went into decline, and there is less evidence for participation in the long distance interaction networks that linked the residents of Bagasra to the wider Indus Civilization. Despite these economic and social changes, the organization of pastoral land-use and associated social networking practices characteristic of Phase 2 continued into Phase 3 largely unchanged. The combination of self-sufficiency and local exchange relationships characteristic of Phase 2 appear to have insulated the residents of Bagasra from the effects of the larger scale changes that mark the transition to Phase 3. In short, it appears that the local scale pastoral land-use practices of Harappan Gujarat were largely sustainable in the face of considerable global scale changes characteristic of the later period of the Indus Civilization.

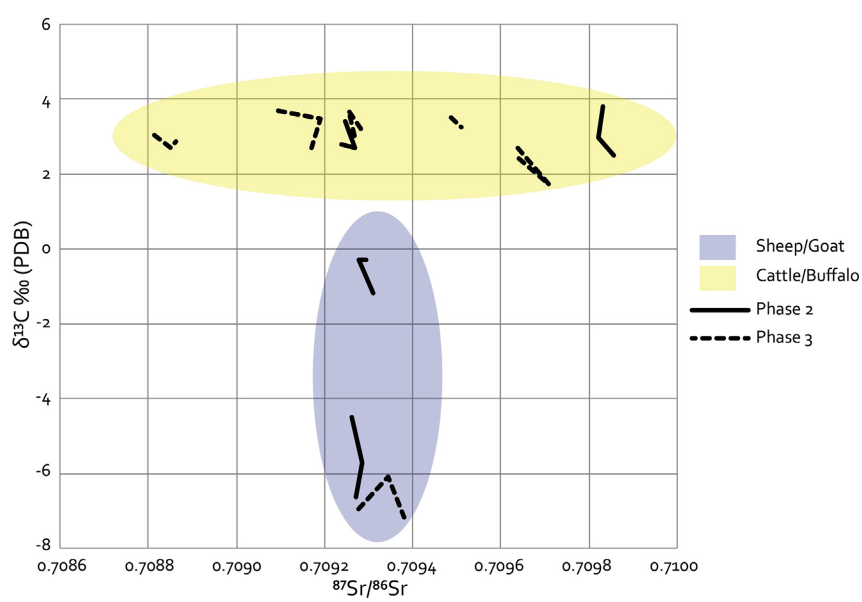


Fig. 9. $^{87}Sr/^{86}Sr$ plotted against $\delta^{13}C$ by taxa and phase. Lines connect the samples from an individual tooth (as shown in Fig. 2).

7. Conclusion

The most basic result of this pilot study has been to demonstrate that analyses of biogenic isotopes have the potential to provide new information on pastoral land-use and associated social networking practices in the context of Harappan Gujarat. The interpretations that we have put forth, however, would not have been possible without comprehensive traditional faunal analyses; the datasets produced by these two approaches are best interpreted in concert. Based upon the positive results presented here, we are expanding this program to include representative samples from Phases 1 and 4 at Bagasra to explore the extent to which pastoral land-use and social networking practices of the sites residents changed from the initial establishment of the site to its eventual abandonment. Analogous materials from other nearby sites including Shikarpur, Jaidak, and Loteshwar will be included to explore inter-site variation in this socially dynamic borderland region. In conjunction with this work, systematic sampling of strontium isotope ratios across the physical landscape will allow for more detailed analyses of livestock mobility patterns—and their associated human social networks. Necessarily incomplete, our results nevertheless establish the empirical baseline necessary for continued studies of the land-use practices of the Indus Civilization in Gujarat and the associated socioenvironmental changes that may have accompanied the emergence and decline of South Asia's first urban civilization.

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